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EFFECT OF SECONDARY INJECTION ON NON–CIRCULAR JETS

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ABSTRACT

Studies on non-circular jets have become a captivating field of interest, since the technique exploits the advantage of the nozzle exit geometry, in terms of mixing characteristics. The supersonic jet mixing can be effectively employed in the injector orifice in a Supersonic Combustion Ramjet (SCRAMJET) engine, looking for shorter combustor lengths that accounts to weight reduction of the engine. This paper puts forward the experimental evaluation of mixing characteristics of supersonic flow through a conical converging-diverging nozzle designed for Mach number 1.8. Circular, blunt square, blunt hexagon and blunt octagon shape exit geometries is reckoned with circular inlet and throat geometries. This is accompanied with an active flow control method (i.e.) secondary injection of air located at 20.42% of the total length of the nozzle from the exit of the nozzle. The impact of the exit geometries and the secondary injection on the potential core is scrutinized by intently studying the pitot pressure decay at the downstream of the nozzle. The experimental study involves the flow of non-reacting fluid (air) as the working fluid and secondary fluid under cold flow conditions. The jet entrainment always occurs at the exit effectively, and mixes with the ambient at a faster rate. The dimensionless pitot pressure is plotted against dimensionless centerline distance under design and off-design conditions. The amplitude of the pressure fluctuations was found to increase at all operating conditions with increasing number of sides in the exit geometry. The shock structures were captured using shadowgraph technique for the above conditions. It is observed that the hexagonal jet with secondary injection at an angle of 90◦ shows 16.79% decrease in supersonic core length among the four exit geometries. The shock diamonds are found to be diminishing at a faster rate in hexagonal jet with secondary injection.

KEYWORDS: Hexagonal Nozzle, Octagonal Nozzle, Jet Entrainment, Potential Core & Shadow Graph Technique

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Original Article

INTRODUCTION

A jet is a pressure-driven shear flow of a fluid to the quiescent ambience, which maintains constant local width to axial distance. High speed jets have taken the interest of researchers in the recent years. There are very little empirical relations to characterize the flow downstream of the nozzle.

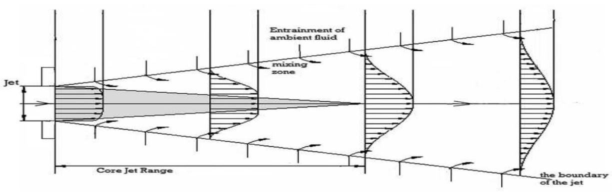
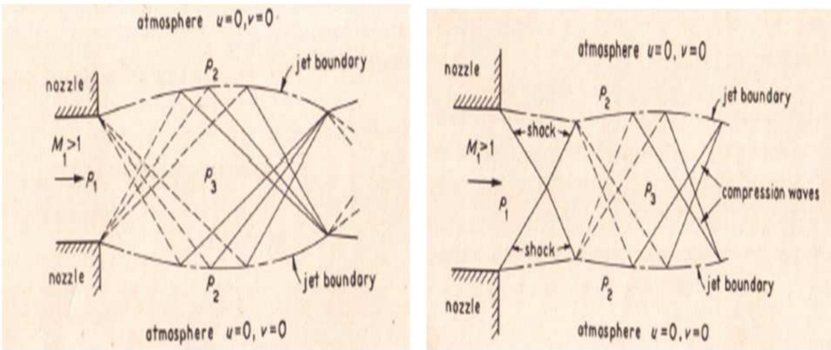


Figure 1: Schematic of the Down Stream Region of Supersonic Jet[9]

The supersonic flow structure is crucial to understand and interpret, as it consists of various complex structures in it. Supersonic flows are characterized by their Mach number being above 1, and fall into the compressible flow regime. Since the boundary layer of the fluid flow cannot sustain a pressure difference, the fluid flows as a free shear layer. The emerging flow from a nozzle contains of four regions namely the core region, transition region, profile similarity region and the termination region as shown in Figure 1. The core region, also known as potential core is the significant phenomenon occurring only in supersonic jets is the zone, where, the centreline velocity is same as that of the outlet velocity. The transition region is the region where, velocity decay starts and the profile similarity region shows self-similar flow that is independent of axial distance [9].

The shock cell comprises of a series of both compression and expansion waves that are formed as a result of the pressure imbalance between the external ambience and the jet exhaust. The supersonic flow past a nozzle may be over-expanded, optimally expanded or under expanded relative to the nozzle pressure ratio maintained during operation of the nozzle as illustrated in Figure 2.



(a) Under Expanded Nozzle (b) Over-Expanded Nozzle

Figure 2: Various Operating Conditions of Supersonic Nozzle [5]

Supersonic combustion has been the contemporary area of research, which puts forward number of unique challenges. One of the major calls for the researchers is making an optimized combustor length. The fuel-air mixing inside the combustion chamber should be enhanced, in order to achieve stable combustion throughout the operating time of the engine, despite the flow residing inside the chamber for only few milliseconds. The combustion in a SCRAMJET engine can be controlled by controlling the mixing of fuel-air inside the combustion chamber and the delay time provided for the fuel injection during operation. A valuable amount of mixing can be initiated by changing the injection methods of fuel into the combustion chamber. Flow past a nozzle can be controlled by active and passive methods like injection of a secondary fluid, placing tabs, wires and change in exit geometries of the supersonic nozzle. One of such methods would be incorporating a supersonic convergent-divergent nozzle that can enhance the mixing downstream of the nozzle exit.

Enhanced mixing takes place in non-circular jets, and thereby reducing the supersonic core length of the flow by comparing circular, square and hexagonal supersonic jets [4]. Also, while comparing the mixing characteristics and velocity decay of circular, hexagonal and cruciform jets, it is found that the hexagonal and cruciform jets show faster mixing and shorter potential core lengths [6]. The significant decrease in the potential core of non-circular jets is found by comparing a notched rectangular orifice and a circular orifice [3]. In single and multiple injectors into the supersonic flow, where different injection angles of 35°, 45°, 60° and 90°, it has been found that lower injection angles provide promising mixing, as it produces less flow disturbance and total pressure loss [1]. The turbulent cross-flow in jet fluid progressively stirs with

the core-flow causing the enhanced jet entrainment. Pressure fluctuations inside the recirculation zone are coupled with large-scale unsteady dynamics of the barrel shock deformation and accompanying large scale vortex formation in the windward direction of the jet boundary [10]. The air flow phenomena occurring during the tests carried out at cold flow conditions resemble that of the reacting flow phenomena, and that the sharp corners in the direction of flow interrupting the coherent structures formed in the supersonic flow [2]. The nozzle shape and orientation play a large-scale role in the mixing of the jet at the downstream of the nozzle using Large Eddy Simulation (LES) [12].

NOZZLE GEOMETRIES

Contoured nozzles are employed, where high Mach numbers are required, which have large values of area-ratio and are expected to have minimum length, accounting the weight of the nozzle. In most cases, the rocket nozzles are contoured as they propel hot gases to a higher Mach numbers. The nozzles are designed for Mach number 1.8 at the exit with circular inlet and throat geometries. The exit geometry deployed in the nozzles are circular, blunt square, hexagonal and octagonal, where the number of sides increase in each model, as shown in Figure 3. The length of the convergent and divergent portions of the supersonic nozzle is optimized to produce Mach number 1.8 at the exit of the nozzle. The nozzle is designed such that, the geometry changes gradually from circular to non-circular, in order to reduce the losses occurring on account of the sudden geometry changes, and also the frictional losses are reduced by optimizing the nozzle length at the divergent portion. The secondary injection is provided at a distance of 20.42% of the total nozzle length from the exit at an angle of 90° to the core flow inside the nozzle [1].The transverse injection of secondary fluid is chosen, in order to ensure enhanced mixing by the formation of eddies, increasing the turbulent kinetic energy downstream of the flow direction [6].

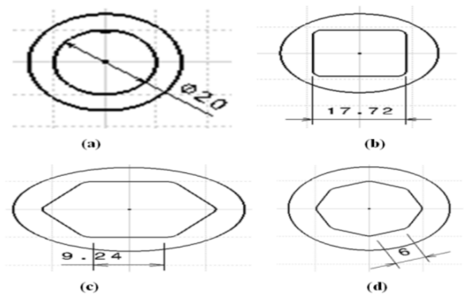


Figure 3: Exit Geometries of the Nozzles
(a) Circular Nozzle
(b) Blunt Square Nozzle
(c) Blunt Hexagonal Nozzle
(d) Blunt Octagonal Nozzle

EXPERIMENTAL SETUP

The experiment was carried out in the Supersonic Jet Facility in the Propulsion Laboratory at Rajalakshmi Engineering College, Thandalam, Chennai as shown in Figure 4. The experimental setup consists of two air compressors; each operating at 950 rpm delivers the required compressed air to a storage tank of capacity 5000 liters working under maximum pressure of 25 bar. A moisture separator is employed to remove the vapor content in the compressed air to eradicate the problems arising due to condensation of the vapor particles during operation. The compressed air is allowed to linearize at the settling chamber, and the pressure in the chamber is controlled using control valves and the pressure is

recorded using a Bourdon pressure gauge.

A pitot probe integrated with a three- dimensional traverse mechanism is employed to measure the total pressure of the jet exhaust in all the three directions, whose data is accumulated using an 8-port pressure transducer that averagely records 150 samples per second [11].

The shadowgraph is captured using a setup as shown in Figure 5, which consists of a lens and light source of optimum intensity. A visible screen is placed at the other side of the lens such that, the shadow of the jet is reflected and falls on the screen. The shock pattern has been observed and photographed using a digital camera of 50 frames per second.

Figure 4: Experimental Setup of Supersonic Jet Facility

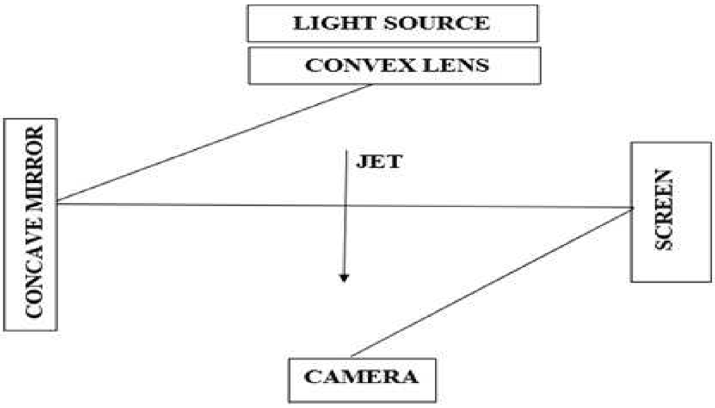


Figure 5: Schematic of Shadowgraph Setup at REC

RESULTS AND DISCUSSIONS

The flow is allowed to pass through the nozzle model to the ambient atmosphere, where, the jet entrains to a certain distance from the exit of the nozzle. The pitot probe senses the total pressures till X/D = 17 along the jet axis. The pitot pressure (P_o) indicating in the pressure scanner corresponds to the total pressure of the flow behind the shock wave formed. This is due to the intrusion of the pitot probe in the direction of the flow. This total pressure measured is non-dimensionalized using the settling chamber pressure (P_{os}). The pressure fluctuations at the entrainment zone are due to the formation of shock cells at the downstream of the nozzle. Because the jet exhaust is moving at a speed greater than

sound, small pressure changes require either shock waves or expansion fans.

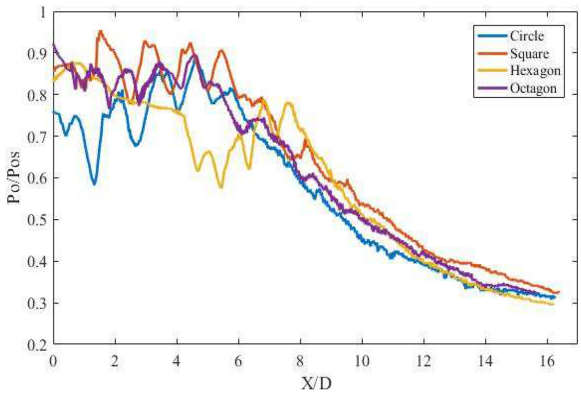


Figure 6: Centerline Pitot Pressure Decay Vs X/D for Different Nozzle Shapes at Over-Expansion Condition (4 bar) Without Secondary Injection

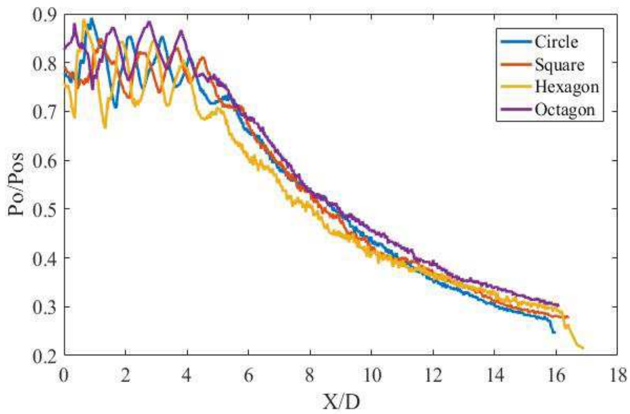


Figure 7: Centerline Pitot Pressure Decay Vs X/D for Different Nozzle Shapes at Over-Expansion Condition (4.8 bar) Without Secondary Injection

The centerline pitot pressure decay is plotted against the X/D for different nozzle shapes under over-expansion conditions at 4.8 bar without secondary injection of air in Figure 6. It is evident from the plot that, the supersonic core length of hexagonal jet is 4.2D from the exit of the nozzle. Comparatively, the hexagonal jet possesses the lowest supersonic core length that proves the improved mixing property of the jet with the ambience.

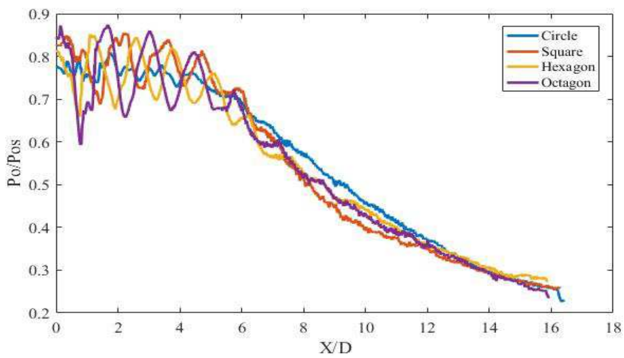


Figure 8: Centerline Pitot Pressure Decay Vs X/D for Different Nozzle Shapes at Optimum-Expansion Condition (5.8 bar) Without Secondary Injection

The pitot pressure versus X/D ratio for design conditions has been compared and plotted in Figure 8. The comparison plots reveal that the square jet performs efficiently under design operative conditions i.e., optimum expansion conditions in terms of mixing. The square jet is found to occupy 5.2D of the jet axis distance from the exit of the nozzle.

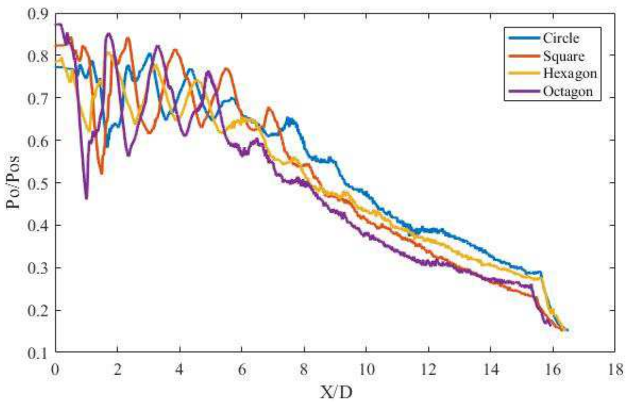


Figure 9: Centerline Pitot Pressure Decay Vs X/D for Different Nozzle Shapes at Under-Expansion Condition (6.8 bar) Without Secondary Injection

Figure 9 illustrates the pitot pressure decay along the centerline of the jet, plotted against X/D for the under-expansion operative condition without secondary injection of air to core flow through the nozzle. The under-expansion condition also reveals that, the hexagonal jet has the smallest supersonic core length of 5.8D from the nozzle exit. In the under-expanded case, the jet expands through Prandtl Meyer expansion, and then it is constrained by a barrel shock and Mach disk. Due to this, counter rotating vortices are generated, which leads to the formation of bow shock at the downstream of the nozzle, this formation of shockwaves influences the rapid mixing of the jet with atmosphere, this characteristic of the jet increases with increase in flow turning angle, hence for this condition, the octagon nozzle has the shortest length for mixing.

The centerline pressure decay has been plotted against X/D of the four nozzle configurations in Figure 10 for over-expanded operating condition with a secondary injection of 2 bar perpendicular to the core flow through the nozzle. Compared to the case without secondary injection, the pressure decay found with secondary injection is effective in terms of mixing rates. It is also evident that, the hexagonal exit geometry shows minimal supersonic core length at the entrainment region. The number of shock cells found in the hexagonal jet is also less than that of the other circular and non-circular jets under same operating conditions.

The distance taken by the jet to mix with ambient is shorter with secondary injection, this is due interaction of jet and the cross flow, which will lead to a formation of complex set of flow structures and vortices, for a circular jet with perpendicular injection to the core flow, it has been found that the Counter-rotating Vortex Pair (CVP) observed to dominate the jet section is related to the pressure field variations in between the upstream and downstream of the jet. These vortices are mainly formed due to impulse created by the interaction of the fluids. At the exit of the nozzle, the shear layer of the jet folds and rolls leading to the formation of vortices.

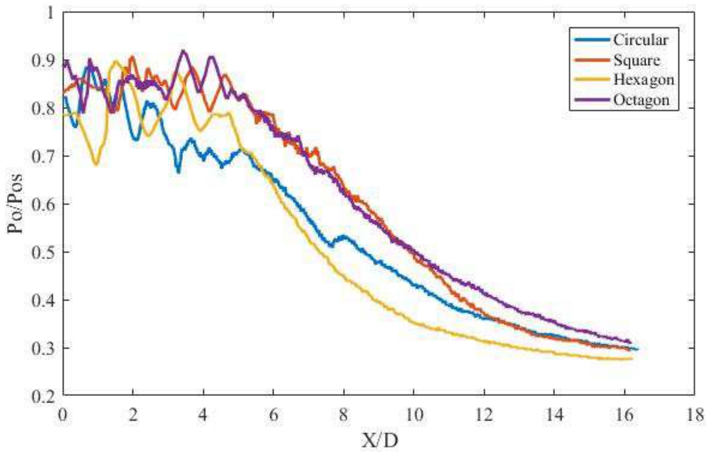


Figure 10: Centerline Pressure Decay Vs X/D for 2 Bar Secondary Injection to 4 Bar Core Flow

The hexagonal exit geometry produces weaker shock than the other geometries, since the shock cell spacing is inversely proportional to mixing characteristics. It has also been found that, when compared with and without injection, the mixing of jets with injection is increased by 6.73%, 7.99%, 30.9% and 2.19 % for circular, blunt square, hexagon and octagon nozzles, respectively.

Table 1: Shock Cell Spacing in Terms of Exit Diameter Without Secondary Injection

EXIT GEOMETRY	4 Bar	4.8 Bar	5.8 Bar	6.8 Bar
Circular	0.50	1.18	0.929	1.21
Blunt Square	0.84	0.40	0.54	1.05
Hexagon	1.00	0.90	1.21	1.49
Octagon	0.39	1.24	1.10	1.06

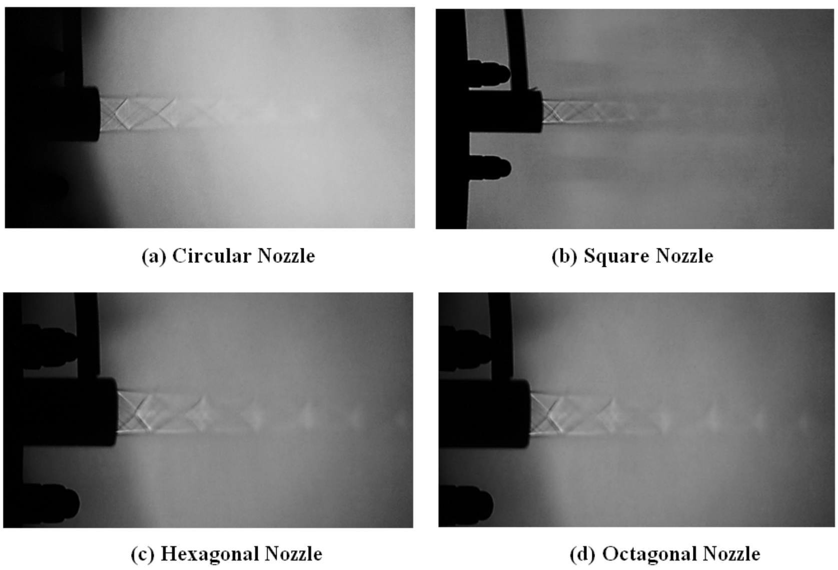


Figure 11: Shock Structure Downstream of Over-Expanded Jets

The over-expanded jet from Circular, Chamfered square, hexagonal and octagonal nozzles have been captured using shadowgraph technique is shown in Figure 11. The shock cells formed at the exit of the nozzle are distinctly visible

near the exit of the nozzle, while the strength of the shock reduces with increase in the distance along the longitudinal axis of the jet. It can be visualized from figure 11 that, the shock cell formed at the exit of the nozzle is equidistant with only the strength of the shocks diminishing.

CONCLUSIONS

Centreline pressure studies were carried out at sea level conditions in the supersonic jet facility, for various operating conditions of the nozzle. Shock structure of the supersonic jets was visualized using shadowgraph technique and suitable recording devices. It is found that, as the number of flow turning points increases, the number of shock diamonds formed are also found to increase. The amplitude of the pressure fluctuations is found to increase at all operating conditions with increasing number of sides in the exit geometry. The hexagonal jet shows decreased potential core of 16.79% compared to the circular, blunt square and octagonal jets in the over-expansion condition with secondary injection. Also, the shock diamonds are found to be diminishing at a faster rate in hexagonal jet with secondary injection. This phenomenon occurs due to the decay of the jet boundary with the ambient surrounding.

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